PCT/GB 2004 / 0 0 4 3 3 4

The Patent Office

INVESTOR IN PEOPLE

The Patent Office
Concept House
Cardiff Road
Newport
South Wales
NP10 8QQ

I, the undersigned, being an officer duly authorised in accordance with Section 74(1) and (4) of the Deregulation & Contracting Out Act 1994, to sign and issue certificates on behalf of the Comptroller-General, hereby certify that annexed hereto is a true copy of the documents as originally filed in connection with the patent application identified therein.

In accordance with the Patents (Companies Re-registration) Rules 1982, if a company named in this certificate and any accompanying documents has re-registered under the Companies Act 1980 with the same name as that with which it was registered immediately before re-registration save for the substitution as, or inclusion as, the last part of the name of the words "public limited company" or their equivalents in Welsh, references to the name of the company in this certificate and any accompanying documents shall be treated as references to the name with which it is so re-registered.

In accordance with the rules, the words "public limited company" may be replaced by p.l.c., plc, P.L.C. or PLC.

Re-registration under the Companies Act does not constitute a new legal entity but merely subjects the company to certain additional company law rules.

Signed

Dated 20 October 2004

BEST AVAILABLE COPY

[redacted]ents Form 1/77

Pa' Act 1977
(Rule 16)

The
Patent
Office

13OCT03 E844094-1 D01038
P01/7700 0.00-0323922.5

Request for grant of a patent

(See the notes on the back of this form. You can also get an explanatory leaflet from the Patent Office to help you fill in this form)

THE PATENT OFFICE
K
11 OCT 2003
NEWPORT

The Patent Office
Cardiff Road
Newport
South Wales
NP10 8QQ

1. Your reference	P304640GB
2. Patent application number *(The Patent Office will fill in this part)*	0323922.5
3. Full name, address and postcode of the or of each applicant *(underline all surnames)*	Aston University Aston Triangle Birmingham B4 7ET United Kingdom
Patents ADP number *(if you know it)*	690162300|
If the applicant is a corporate body, give the country/state of its incorporation	
4. Title of the invention	Laser Inscription of Optical Structures in Laser Crystals
5. Name of your agent *(if you have one)* "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	WITHERS & ROGERS Goldings House 2 Hays Lane London SE1 2HW
Patents ADP number *(if you know it)*	1776001

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or each of these earlier applications and *(if you know it)* the or each application number	Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application	Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(answer 'Yes' if:* *a) any applicant named in part 3 is not an inventor, or* *b) there is an inventor who is not named as an applicant, or* *c) any named applicant is a corporate body.* *See note (d))*	YES

9. ..er the number of sheets for any of the following items you are filing with this form. Do not count copies of the same document

Continuation sheets of this form	
Description	12
Claim*(s)*	6
Abstract	1
Drawing *(s)*	13 + 13

10. If you are also filing any of the following, state how many against each item.

Priority documents	-
Translations of priority documents	-
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	-
Request for preliminary examination and search *(Patents Form 9/77)*	-
Request for substantive examination *(Patents Form 10/77)*	-
Any other documents *(please specify)*	-

11. I/We request the grant of a patent on the basis of this application.

Signature WITHERS & ROGERS Date 10 October 2003

12. Name and daytime telephone number of person to contact in the United Kingdom — Dr Karl Barnfather 0121 245 3900

Warning

After an application for a patent has been filed, the Comptroller of the Patent Office will consider whether publication or communication of the invention should be prohibited or restricted under Section 22 of the Patents Act 1977. You will be informed if it is necessary to prohibit or restrict your invention in this way. Furthermore, if you live in the United Kingdom, Section 23 of the Patents Act 1977 stops you from applying for a patent abroad without first getting written permission from the Patent Office unless an application has been filed at least six weeks beforehand in the United Kingdom for a patent for the same invention and either no direction prohibiting publication or communication has been given, or any such direction has been revoked.

Notes

a) *If you need help to fill in this form or you have any questions, please contact the Patent Office on 0645 500 505.*
b) *Write your answers in capital letters using black ink or you may type them.*
c) *If there is not enough space for all the relevant details on any part of this form, please continue on a separate sheet of paper and write "see continuation sheet" in the relevant part(s). Any continuation sheet should be attached to this form*
d) *If you have answered 'Yes' Patents Form 7/77 will need to be filed.*
e) *Once you have filled in the form you must remember to sign and date it.*
f) *For details of the fee and ways to pay please contact the Patent Office.*

P304640GB

Laser Inscription of Optical Structures in Crystals

This invention relates to methods of altering the refractive index of portions of and inscribing optical structures in, materials such as crystals by laser irradiation, and to laser inscribed crystals, particularly but not exclusively, laser crystals.

It is known to attempt to form wave guides within crystal media. Providing waveguides within crystals has multiple applications but is particularly useful in laser crystals for solid state lasers. Common problems with some laser crystals such as Ti:Al_20_3, and Cr doped Yttrium Aluminium Garnet (YAG), are a relatively low optical gain and ineffective pumping of the crystal. Consequently it is difficult to design a laser cavity with such crystals, capable of effective light pumping and having low loss of a signal wavelength. It is much easier to obtain this combination of features with a laser cavity having waveguides on or in the laser crystals rather than using surrounding bulk optics.

Formation of waveguides in laser crystal media is conventionally difficult. One current method is to build an epitaxial layer on top of a crystal of different refractive index to the crystal which will form a waveguide at the interface. An alternative method is to attempt to create a region of differing refractive index near the surface of a laser crystal by diffusion. Due to these methods of fabrication the waveguide is necessarily at or near the surface of the crystal and not deeply embedded or within the bulk of the crystal.

All of the conventional methods involve processing in a vacuum adding to cost, deliver limited quality waveguides and are restricted geometrically as the waveguide can only be formed at the crystal surface or close very close to the surface. Waveguides created by such methods are typically within 10 μm of the surface of the crystal.

It is also known to inscribe optical structures such as waveguides into some glasses such as borosilicate glass, as described in US Patent application 2002/0076655 A1. In

this process a femtosecond pulse laser is used to increase the refractive index of the glass at a focus point and this point is translated in order to form optical structures. Using such specialist techniques like those disclosed in US 2002/0076655 it is possible to create these optical structures without causing breakdown damage of the glass. These inscribed pieces of glass have for example been suggested for use in fibre optic technologies where the need to guide light by using different refractive indexes of glass is common. Whilst the detailed physics explaining why and how the refractive index is changed by the focussed laser is not fully understood at present, it is known to effect different materials differently.

Present experience and understanding of the physics suggest that such laser inscribing positive change in refractive index is particular to certain amorphous glasses. Accordingly, this technique while effective at creating waveguides in glass has not been seen as being a useful tool in creating waveguides in crystals or to improving laser cavities. In particular the change in refractive index is thought to be due to rearrangement of the molecular structure of that portion of the glass. The strong lattice structure of crystals suggest this would be difficult if not impossible to accomplish in crystals and if a change is effected may damage the crystal structure so as not to be suitable for optics.

It is an object of the present invention to improve the existing methods of creating optical structures within crystals, providing different refractive indices within a crystal, and to provide crystal and laser crystals with more complex optical structures.

Accordingly to the first aspect of the invention there is provided a method of altering the refractive index of a portion of a crystal comprising focusing a pulsed laser beam at a desired position within the crystal and moving the focused beam along a path such that the focussed beam alters the refractive index of the portion of the crystal along the path.

According to a second aspect of the invention there is provided a crystal comprising an inscribed structure wherein the structure has a different refractive index to the rest of the crystal.

According to a third aspect of the invention there is provided a method of producing a multicore waveguide, comprising a plurality of coupled single waveguides, in a material, comprising the steps of,
focusing a pulsed laser beam at a desired position within the material and moving the focused beam along a path such that the focussed beam alters the refractive index of the region of the material along the path,
and refocusing a pulsed laser beam at a second desired position within the material and moving the focused beam along a second path separated from the first path such that the focussed beam alters the refractive index of the region of the material along the second path.

Embodiments and methods of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of equipment which can be used in a method of performing the invention to inscribe optical structures;

Figure 2 is a view of an example of an inscribed predetermined path of a focussed laser formed in accordance with the invention;

Figure 3a is a microscopic view of an inscribed single waveguide,

Figure 3b is a view of the near field profile of an inscribed waveguide.

Figure 3c is a cross section of the near field measured of Figure 3b in plane X,

Figure 3d is a cross section of the near field measured of Figure 3b in plane Y,

Figure 3e is a view of the near field profile of a different inscribed waveguide.

Figure 3f is a cross section of the near field measured of Figure 3e in plane X,

Figure 3g is a cross section of the near field measured of Figure 3e in plane Y,

Figure 4a is a top down view of an inscribed multicore waveguide,

Figure 4b is a view of the near field profile of inscribed an multicore waveguide,

Figure 4c is a cross section of the near field measured of Figure 4b in plane X,

Figure 4d is a cross section of the near field measured of Figure 4b in plane Y,

Figure 5a a schematic view of a crystal comprising an optical coupler according to the invention;

Figure 5b a schematic view of a crystal comprising a Y coupler according to the invention;

Figure 6 is a schematic view of a laser crystal comprising a diffraction grating according to the invention, and

Figure 7 is a schematic diagram of surface based and 3D gratings in a multicore waveguide

In Figure 1 is shown a schematic arrangement of equipment 10 suitable for practising the invention. The equipment 10 comprises a laser 12, a lens 14, a crystal 16 and translation device 19. A pulsed laser beam LB is generated by the laser 12.

The pulse laser beam LB is focused by lens 14 to a focus 20 situated in the crystal 16. As depicted in Figure 1 the focus 20 is below a front surface 17 of the crystal nearest the laser 12 and above a rear surface 18 of the crystal furthest from the laser 12.

The intensity of the beam LB at focus 20 is far greater than at any other point along its length. Consequently, localised alteration of the refractive index of the crystal 16 is caused by the high intensity of the laser beam LB at focus 20.

The translation device 19, which can be for example a three coordinate micrometric translation stage, is used to move the crystal 16 three dimensionally in any of the X, Y or Z directions as shown in Figure 1. Using this movement the focus 20 of the laser beam LB can be moved relative to the crystal 16 along a predetermined path. Figure 2 shows an example of such a predetermined path 24 moving from an initial focus 20 at coordinates XYZ to a finishing focus 22 at co-ordinates X'Y'Z'.

Coinciding with the path along which the focus 20/22 has been moved there is a created region along path 24 of altered refractive index. Since the region 24 has a different refractive index from the remainder of the crystal 16, the region forms an optical structure that can be used to guide light. In the example in Figure 2 the optical structure formed extends in three dimensions between the starting and ending points 20 and 22, in the crystal 16.

In one particular example of the invention, the laser 12 can be a regenerated femtosecond amplifier (such as a Spitfire laser available from Spectra-Physics, Inc) operated at a wavelength of 800 nm with a pulse duration of 120 fs, a pulse frequency of 1 kilohertz and a pulse energy of 0.5 mJ.

Such a specification of laser 12 can be effectively used on a chromiun doped YAG crystal including YAG: Cr^{4+} ($Y_3Al_5O_{12}$) and Cr^{3+} ($Y_3Al_5O_{12}$). It can also be used on Titanium or Cr^{3+} doped Sapphire Ti:Al_2O_3 , Chromium doped Forsteryte (Cr^{3+}:Mg_2SiO_4, Cr^{4+}:Mg_2SiO_4), Neodymium doped Vanadate ($Nd^{3+}YV0_4$), Cr^{3+} and Nd^{3+} doped GSGG, Cr^{3+} doped Li (Ca/Sr) AlF_6 and Neodymium Yb^{3+}, Er $^{3+}$, Tm or Al^{3+} doped YAG .

A chromium doped YAG crystal 16 should also have additional co-dopants introduced in order to stabilise the active Cr^{4+} ions such as with Mg^{2+} or Ca^{2+} possibly with residual

Cr^{3+}. Co-dopants, such as Mg^{2+} ions, can also be used to stabilise active Cr3+ ions in YAG. The additional doping facilitates formation of point defects, and in particular oxygen vacancies in the lattice, within the crystal 16. The processes associated with the high density exposure to a femtosecond beam caused by the invention probably significally changes concentration of these defects thus making YAG Cr^{4+} with additional dopants particularly well suited to inscription according to the invention.

It is thought that laser inscription of waveguides using the methods described would probably not be possible in a theoretical perfect crystal. It is thought that point defects such as the oxygen deficient defects in Chromium doped YAG facilitate the structural change under laser irradiation which allows waveguides to form such as by molecular rearrangement. Consequently laser crystals for inscription should contain point defects/dislocations and therefore the invention is best suited to doped crystals with corresponding defects/dislocations. The laser crystal to be inscribed preferably contain vacancies in the lattice allowing easier structural change around these vacancies.
Preferably when the invention is carried out with the combination of particular laser 12 and YAG crystal 16 described above, the lens 14 is a microscope objective with a numerical aperture in the range 0.2 to 0.65. With these particular laser 12, lens 14 and crystal 16 an example of the focus of the crystal 16 is about 0.3 to 4 millimetres and the estimated spot diameter at the focus is from 1 micrometer to about 10 micrometers.

In general the laser wavelength and crystal 16 are selected to minimise optical linear absorption of the laser beam LB by the crystal 16. Accordingly, the wavelength of the laser for YAG is in the range of about 1.35 to 1.57 μm in the near infra red range. Within these wavelengths absorption the beam by the crystal 16 is very low. The specific range of wavelengths in which suitable inscription of the crystal will occur is dependent on the extent of doping and on the specific material.

Time duration of each pulse is around 120 fs and typically in the range 100 to 200 fs which is significantly less than thermal diffusion time of the crystal 16 and the frequency of the pulses is around 1 kHz. The invention could also be realised with a

pulse duration in the range 30-300 fs and a repetition rate in range from 0 to at least 1 MHz.

The period of pulses of the laser 12 is preferably selected to be significantly greater than the thermal diffusion time of the crystal 16. This allows each pulse to heat the material independently of the other pulses and helps to avoid the intensity or temperature on any part of the crystal 16 becoming too high, thereby preventing matter interaction of the dense plasma of free electrons from occurring outside of the locality of the focus 20. The intensity of the laser 12 is preferably chosen to be greater than the threshold to form free electron plasma but less than the laser breakdown or damage intensity of the crystal 16. The intensity of the laser at the surface of the crystal should also be preferably kept below the surface damage threshold.

The exact intensity of the laser used is dependent on how tightly focussed the laser beam LB is at the focus 20. The more focussed the laser the lower the energy need be. For example the diameter of the laser beam LB at the focus is preferably between 1 and 10 to 30 μm but could be up to 100 μm and still effect change of the refractive index.

Translation of the device 19 is preferably done at a speed to prevent the same region or localities receiving excessive numbers of pulses.

In an alternative method instead of the crystal 16 being translated, the laser 12 can be translated using a device similar to translation device 19.

Whether the refractive index of a region 24 produced using the method described above causes an increase or decrease in the refractive index relative to the remainder of the crystal 16 depends on the crystal material used. The amount by which the refractive index is changed depends on the particular crystal material but also on the intensity of the laser beam LB. After a region 24 has been produced as described above in a crystal 16 by laser 12 it is possible to measure the magnitude of the change of refractive index.

A positive change in the refractive index is achieved in Chromium doped YAG, Titanium doped Sapphire and suitable laser crystals. Materials in which a positive change in refractive index occurs are much more suitable for the creation of waveguides and other more complex optical structures since the region that has been altered will act as a waveguide.

The change in refractive index of the particular crystal 16 can be determined as a function of the laser beam intensity, and once this is done the optical structures can be created using regions 24 in the crystal 16 with the refractive indices altered by a predetermined/precalculated amount. The refractive index can also be varied along the region 24 by modulating the intensity of the laser 12 during translation of the focus 20 through the crystal 16.

Where the refractive index has been increased in the material, any altered region 24 of longitudinal extent becomes an effective waveguide surrounded by material of low refractive index i.e. the remainder of the crystal 16. In a crystal material where the refractive index is decreased by the laser inscription, waveguides can be formed by bordering or surrounding unaltered regions of the crystal 16 with altered regions 24 and so creating a region surrounded by a lower refractive index.

The altered region 24 can be created remote form the surface of the crystal 16 at depths exceeding and indeed far exceeding 10 mm. The region 24 can be created at any depth below the crystal surface providing optical equipment such as lens 14 is provided which is capable of focussing the laser beam LB at the required depth within the crystal 16.

In Figure 3a is shown a microscope view of a single waveguide inscribed by the process described above in YAG:Cr(0.05%)Mg(0.25%).

In Figures 3b and 3e is shown the near field profiles of two separate single waveguides produced in YAG:Cr(0.05%)Mg(0.25%), which were inscribed under different conditions. The waveguide shown in Figure 3b was produced with an average laser power of 13.7 mW and a sample translation speed 0.5 mm/s whereas the waveguide

shown in Figure 3b was produced with an average laser power of 10.1 mW and a sample translation speed 0.05 mm/s. The scale of Figures 3b and 3e is 100 μm across the horizontal and 60 μm in the vertical and the wavelength of light is 632 nm.

The waveguide shown in Figure 3b can be seen as having multimode profile with two distinct similarly sized modes 30 and 32 shown in the near field profile. Figures 3c and 3d shows cross sections of the near field profile of Figure 3b. In Figure 3d two distinct peaks 33 and 34 can be seen representing the modes 30 and 32.

The near field profile in Figures 3e, f and g though shows that the waveguide made in the same material but with a different power and sample speed has a profile similar to a single mode being dominated by a single large mode 36.

The laser inscription can also be used to make a multicore waveguide comprising a number of coupled waveguides and a microscopic view of an example is shown in Figures 4a and 4b. Structures with 30 or more waveguides can be produced. Such structures with several coupled waveguides can be used to operate as a carrier of one or more common supermodes when the waveguides are phase dependent (when phase of the field of each separate waveguide is dependent upon others).

A larger mode, such as the supermode that can be used with multicore waveguides, has several advantages particularly for in a laser crystal. Large mode sizes allow efficient pumping by a multimode fibre, so that a laser crystal with a large mode allows the use of high-power laser diode pumps. A large mode size is advantageous for short-pulse operation as it minimises effects of non-linear processes. It also allows for reduced saturation of the laser medium which can be an advantage in certain configurations of laser.

In figures 4b, c and d is shown the near field profile of a multicore waveguide. The multicore waveguide has ten waveguide tracks separated by 3.5 μm. As is shown the

profile represents a single super mode 38 despite the presence of multiple tracks or cores.

It has also been found that such multicore waveguides can have reduced losses associated with micro-bending and/or edge effects compared to single waveguides.

Single waveguides produced by inscription either in accordance with this invention or in glass may a strongly elliptical cross section as a result of the particular focusing conditions and exposure regime. In the same conditions, several suitably placed single cores with elliptical or other elongate cross sections can be combined to form a multicore waveguide supporting a quasi-circular supermode.

Multicore waveguides can be produced in suitable crystals using laser inscription with a mode size in the range of 30-100 μm and above with either elliptical a near circular shape.

To produce a multicore waveguide first a single waveguide region is produced using the method described with reference to Figures 1 and 2 creating a waveguide region along a first dimension. The focus of the laser is then moved away from the first waveguide region its position being precisely controlled through another dimension (preferably substantially perpendicular to the first) . This movement of the "focus" is preferably done so that the region along the second dimension along which it has moved is not altered in refractive index this can be done by temporarily lowering the power of the laser, translating the beam and crystal relative to each other at sufficient speed so that alteration of the crystal does not occur or by turning off the laser during the movement so that it is not a focus of the laser that is moved but the theoretical position where it is calculated that the focus would occur if the laser was on.

When the focus/position of potential focus is the required distance from the first altered region the operation is repeated with a second waveguide region of altered, preferably increased, refractive index being created using the method described with reference to Figures 1 and 2. Preferably the focus is not translated through the second (preferably perpendicular) direction during creation of the second region and consequently the two

regions will be a constant distance apart throughout their lengths. In particularly preferred embodiments the two regions have equivalent paths i.e. if the first region starts at coordinates x, y, z and the second at x +1, y+ 1 , z then the end points *is* x', y', z' and x'+1, y'+1 and z' respectively. In the example shown in Figures 5a and 5b the waveguide paths are substantially straight and parallel with all of the waveguide paths lying in the same plane.

This process can then be continued with the focus being shifted repeatedly along the second dimension with several waveguide regions being created.

It has been found that this method of creating multicore waveguides can also be used effectively in glasses.

As well as two and three dimensional waveguides other and more complex optical structures can be formed in a crystal 16 using the invention. Examples of more complex optical structures that can be formed are optical couplers shown in Figure 9, diffraction gratings shown in Figure 10, selective reflectors, loop mirrors, amplifiers and complex shaped regions such as helical regions.

In Figure 5A is shown an optical coupler 40, comprising two waveguiding regions 42 and 44 formed using the method of the invention. In a central portion 46 the waveguiding regions are close enough for coupling to occur. A star coupler comprise more waveguiding regions can be made in a similar manner.

In Figure 5B is shown a Y-coupler 50 comprising branch regions 52 and 54 and a main region 56 All of the regions 52, 54 and 56 are formed using the method of the invention using laser inscription and in this example formed in a laser crystal.16 in which the regions have an increased refractive index.

In Figure 6 a waveguide region 60 leads to laser inscribed lines 62. It is possible to use the laser source at 12 to provide sufficiently small spaces between the lines 62 so that the lines act as grating lines for the tunneled optical structure 64 and therefore to act as

a diffraction grating. Such lines 62 can be produced as either surface based grating or a Bragg grating distributed along the waveguide. When used with single mode structures gratings can be used to provide very precise spectral control and/or pump to signal discrimination.

In Figure 7 is shown a grating structure produced for a multicore waveguide. A mulitcore waveguide region 70, comprising a plurality of parallel core regions 71, leads to periodic surface structure 72. The structure 72 may for example consist of laser inscribed lines similar to lines 62 to act as a diffraction grating. As is shown in Figure 7 the supermode 74 of the waveguide 70 can extend across the whole of the periodic surface structure 72.

Three dimensional gratings together with Fresnel lens like surface relief elements can be used with the multicore waveguide 70 to provide spatial mode control and partial spectral control.

Waveguides and other optical structures such as selective reflectors can be formed by refractive index change of regions of a laser crystal in a predetermined manner using the methods described above. Such an inscribed laser crystal can be used as a component for building a highly effective compact laser cavity. It is possible to create an entire simple laser cavity within a suitable crystal. Crystals such as YAG's and Ti:AL_20_3 can have such optical structures produced in them in order to produce a laser crystal with a higher optical gain.

Claims

1. A method of altering the refractive index of a region of a crystal comprising focusing a pulsed laser beam at a desired position within the crystal and moving the focused beam along a path such that the focussed beam alters the refractive index of the region of the crystal along the path.

2. A method according to claim 1 in which the refractive index of the region is increased.

3. A method according to claim 1 or 2 in which the altered region of the crystal comprises a waveguide.

4. A method according to claim 1, 2 or 3 comprising the steps of moving the focussed beam along multiple paths to create a diffraction grating within the crystal.

5. A method according to claim 1, 2 or 3 comprising the steps of moving the focussed beam to create a selective reflector within the crystal.

6. A method according to any preceding claim in which at least part of the region of altered refractive index is created remote from the surfaces of the crystal, preferably at a distance of more than 10 µm.

7 A method according to claim 6 wherein the region is created at variable depth from the surfaces of the crystal and preferably forms a three dimensional light guiding structure within the crystal.

8. A method according to any preceding claim in which the refractive index of the region is altered by a predetermined amount and preferably increased.

9. A method according to claim 8 in which the intensity of the light beam is modulated whilst the focussed beam is moved modulating the predetermined change to the refractive index which is proportional to the intensity.

10.A method according to any preceding claim in which no laser-induced breakdown of the crystal in the path has occurred.

11. A method according to any preceding claim wherein the crystal on which the laser is focussed is a laser crystal suitable for use in producing a laser.

12. A method according to claim 11 in which the laser crystal is YAG, Forsteryte, Vanadate, LiSAF, GSGG or Sapphire .

13. A method according to claim 11 or 12 in which the laser crystal is doped, preferably with a metal.

14. A method according to claim 12 or 13 in which the laser crystal is chromium doped, Titanium doped, Tm, Er, Yb or neodymium doped.

15. A method according to claim 14 in which the laser crystal has additional co-doping.

16. A method according to any of claims 11 to 15 in which the laser crystal contains a number of point defects, preferably a substantial number and/or preferably vacancy defects.

17. A method according to any preceding claim in which multiple regions of altered refractive index are created at multiple different depths within the crystal.

18. A method according to any preceding claim wherein the light beam used is a pulsed laser.

19. A method according to claim 18 wherein the pulsed laser is a femtosecond laser with a pulse duration of below 200 fs and preferably around 120 fs.

20. A method according to claim 18 or 19 wherein the laser is operated at wavelength of between 1.35 μm and 1.57 μm, and preferably 1.5 μm, and/or at a wavelength chosen to minimise linear absorption by the crystal.

21. A method according to any of claims 18 to 20 wherein the laser has a pulse frequency of between 0.5 And 1.5 kHz and preferably around 1 kHz.

22. A method according to any of claims 18 to 21 wherein the laser has a pulse energy of around 0.5mJ.

23. A method according to any preceding claim in which the beam is focussed by a microscope objective preferably with a numerical aperture in the range 0.2 to 0.65.

24. A method according to any preceding claim in which the focussed beam is moved periodically along the path.

25. A laser cavity at least part of which and preferably all is made by the method of any preceding claim.

26 A crystal comprising an inscribed optical structure wherein the structure has a different refractive index to the rest of the crystal and preferably a higher refractive index.

27. A laser crystal for producing a laser beam comprising the crystal of claim 26.

28.. A laser cavity comprising the crystal of claim 26 or 27.

29. A crystal according to any of claims 26 to 27 in which the crystal is YAG, Forsteryte, Vanadate, LiSAF, GSGG or Sapphire.

30. A crystal according to any of claims 26 to 29 in which crystal is doped with a metal and preferably Chromium, Titanium, Tm, Er, Yb or Neodymium doped.

31. A crystal according to any of claims 26 to 30 in which the crystal has additional doping and preferably with Magnesium or Calcium.

32. A crystal according to any of claims 26 to 31 wherein at least part of the optical structure is remote from the surfaces of the crystal.

33. A crystal according to claim 32 wherein at least part of the optical structure is at a depth of over 10 μm from the surface of the crystal and preferably over 100 μm.

34 . A crystal according to any of claims 26 to 33 wherein the optical structure is surrounded on all sides by non-inscribed crystal of uniform refractive index and forming part of the same lattice.

35. A crystal according to any of claims 26 to 34 wherein the optical structure is three dimensional/ has a variable depth with respect to surfaces of the crystal.

36. A crystal according to any of claims 26 to 35 wherein the optical structure comprises a waveguide.

37. A crystal according to claim 36 wherein the optical structure comprises a mulitcore waveguide having a plurality of coupled single waveguides.

38. A crystal according to claim 37 wherein the multicore waveguide is capable of operating as carrier of a common supermode.

39. A crystal according to claim 37 or 38 wherein the plurality of coupled single waveguides are each separated by less than 5 μm and preferably separated by around 3.5 μm.

40. A crystal according to any of claims 26 to 39 wherein the optical structure comprises a diffraction grating.

41. A crystal according to any of claims 26 to 40 wherein the optical structure comprises a selective reflector.

42. A crystal according to any of claims 26 to 41 wherein the optical structure comprises an optical coupler.

43. A crystal according to any of claims 26 to 42 wherein the optical structure has a lower refractive index than rest of crystal.

44. A crystal according to any of claims 26 to 43 wherein the material of the optical structure is part of the crystal and has not broken down.

45 . A crystal according to any of claim 26 to 44 wherein the optical structures comprises a plurality of tunnel regions which passing above or on the side of each other inside the crystal.

46. A crystal according to any of claims 25 to 45 having an increased quantity of defects throughout the crystal.

47. A crystal according to claim 46 wherein the defects comprise one or more of point defect such as vacancies, interstitial defects and substitutional impurity defects. .

48. Crystal according to claim 46 wherein the defects comprise dislocations.

49. Crystal according to claim 48 wherein concentration of point defects is in the range 10^{18} - 10^{21} cm^{-3}.

50. Crystal according to claim 48 or 49 wherein concentration of dislocations is in the range 10^{7} - 10^{11} cm^{-2}.

51. A method of producing a multicore waveguide, comprising a plurality of coupled single waveguides, in a material, comprising the steps of,
focusing a pulsed laser beam at a desired position within the material and moving the focused beam along a path such that the focussed beam alters the refractive index of the region of the material along the path,
and refocusing a pulsed laser beam at a second desired position within the material and moving the focused beam along a second path separated from the first path such that the focussed beam alters the refractive index of the region of the material along the second path.

52. A method according to claim 51 in which the first and second paths are separated by a substantially constant distance.

53. A method according to claim 51 or 52 wherein the multicore waveguide is capable of operating as carrier of a common supermode.

54. A method according to claim 51, 52 or 53 wherein the plurality of coupled single waveguides are each separated by less than 5 μm and preferably separated by around 3.5 μm.

55. A method according to any of claims 51 to 54 wherein the step of refocusing and creating an additional altered region along an additional path is repeated 10 or preferably 20 times to produce a multicore waveguide comprising 10 or preferably 20 coupled single waveguides

56. A method according to any of claims 51 to 55 wherein the material comprises a crystal.

ABSTRACT

A method of altering the refractive index of a region of a crystal comprising focusing a pulsed laser beam at a desired position within the crystal and moving the focused beam along a path such that the focussed beam alters the refractive index of the region of the crystal along the path.

Figure 1

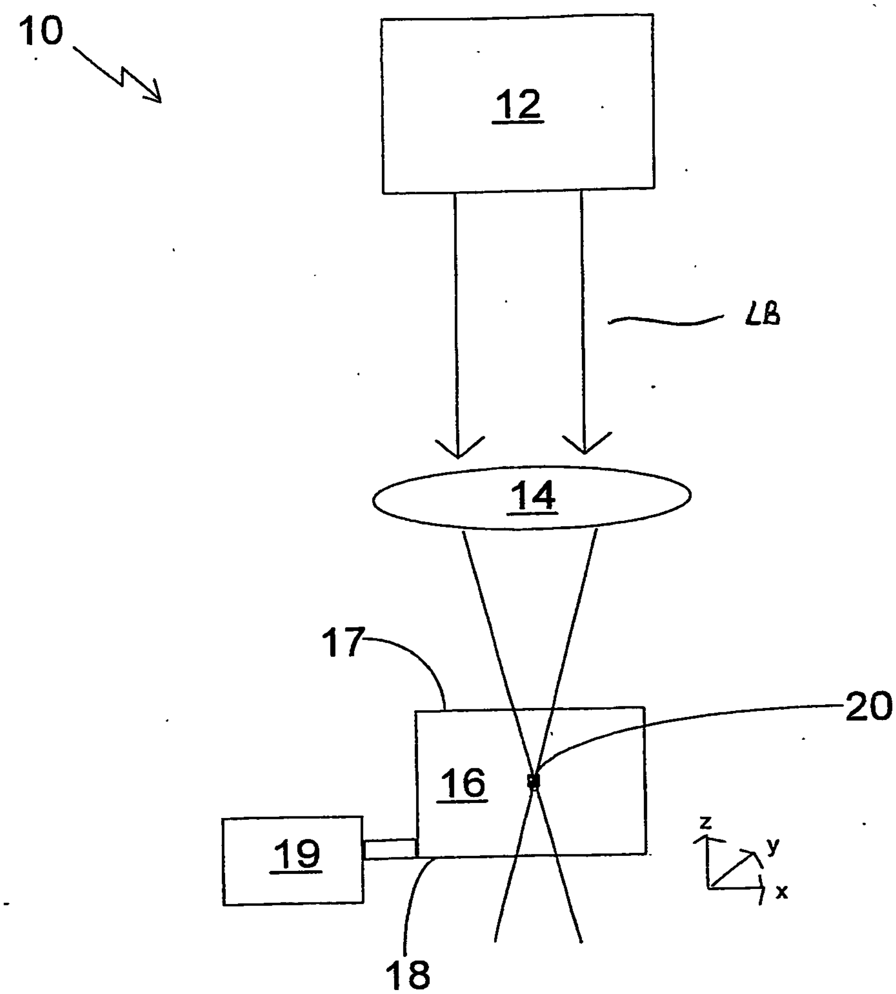


Figure 2

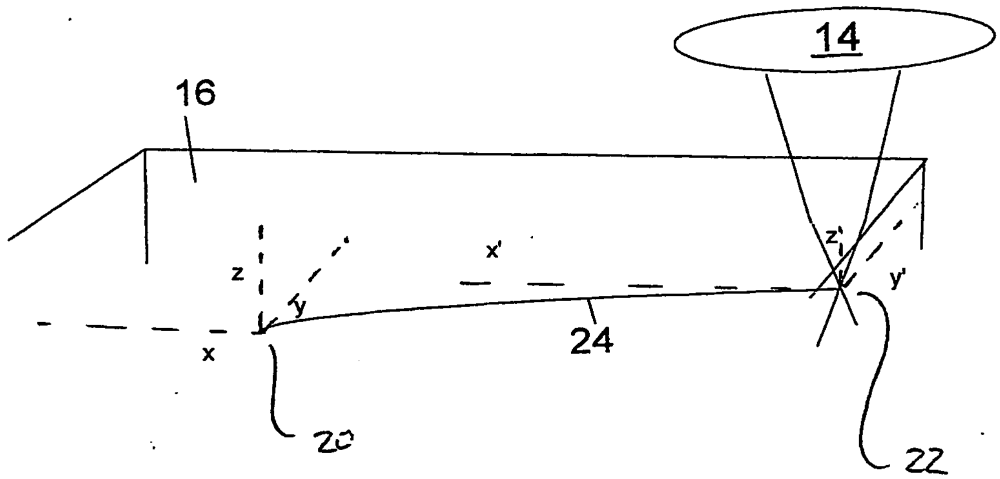


Figure 3a

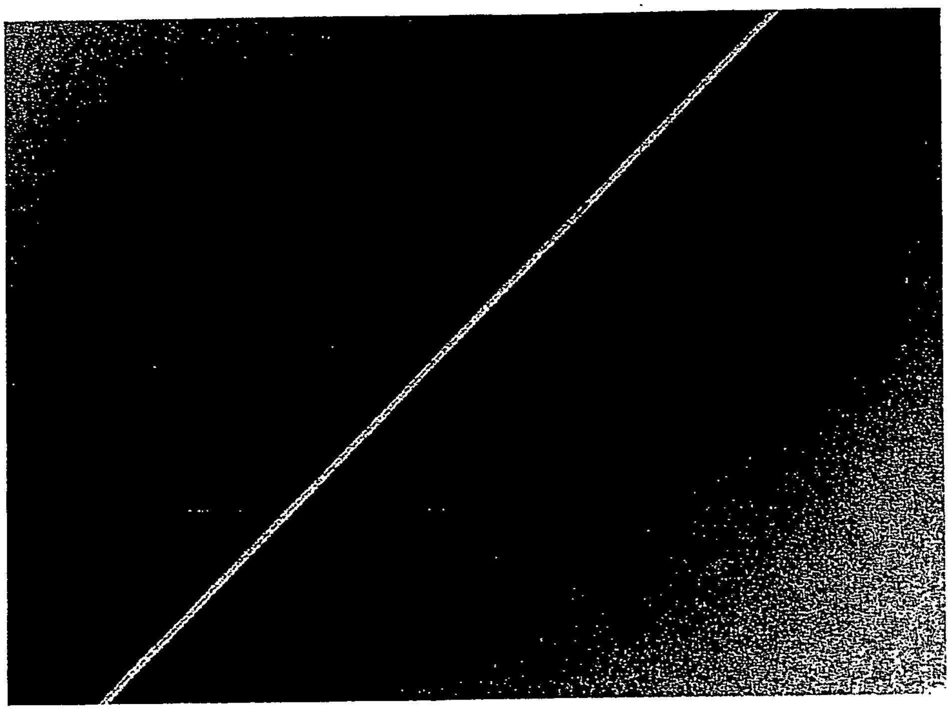


Figure 3b

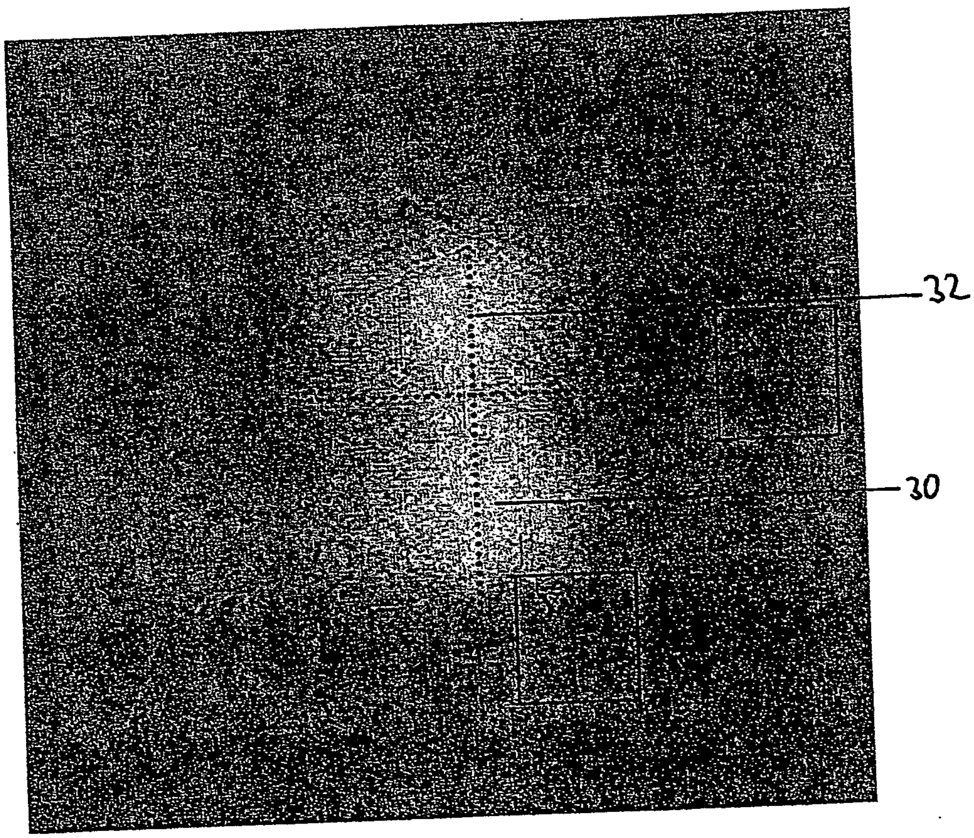


Figure 3c

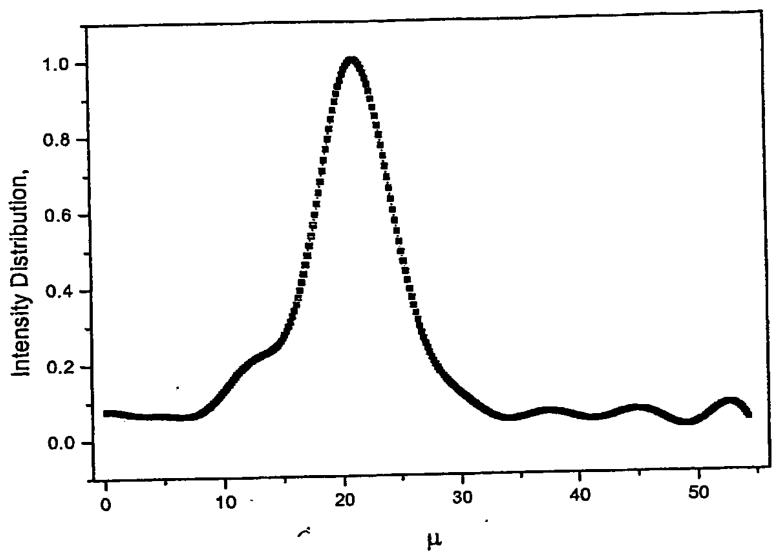


Figure 3d

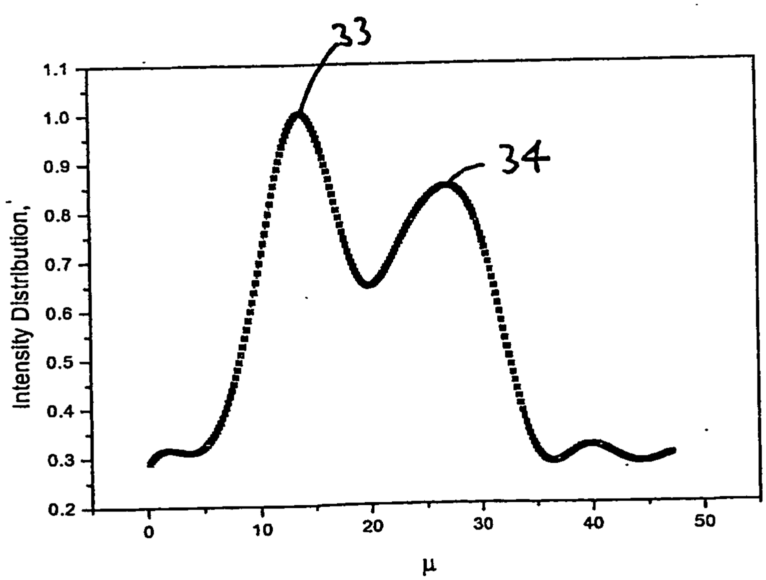


Figure 3e

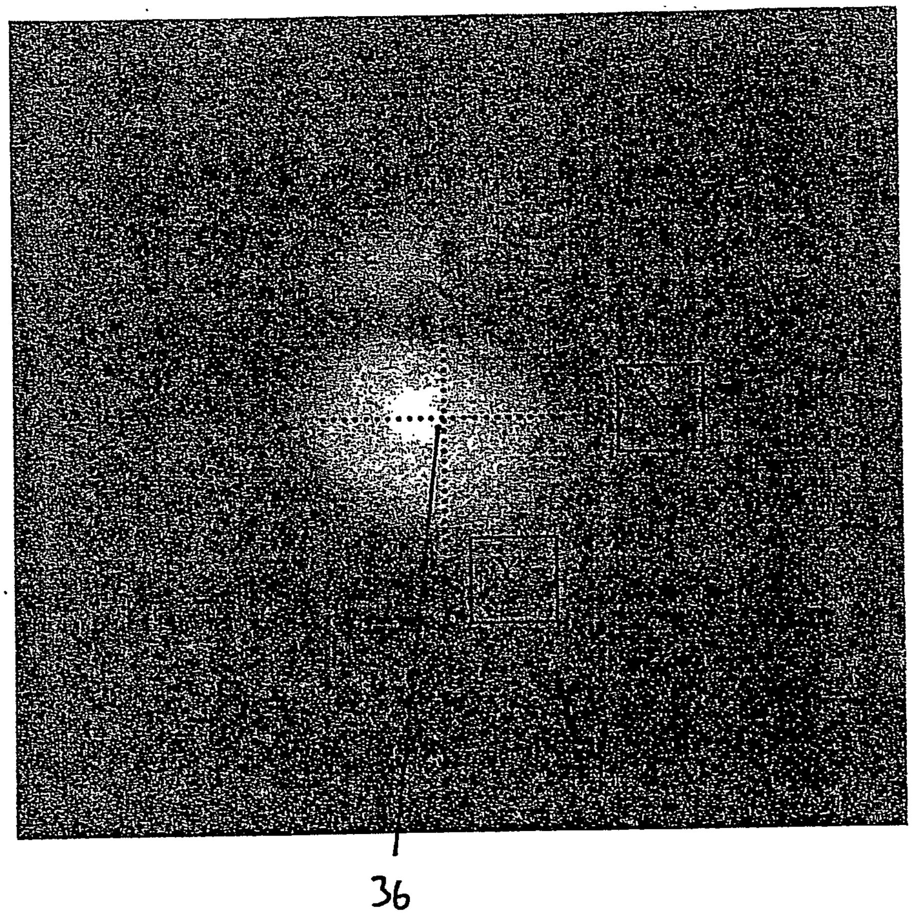


Figure 3f

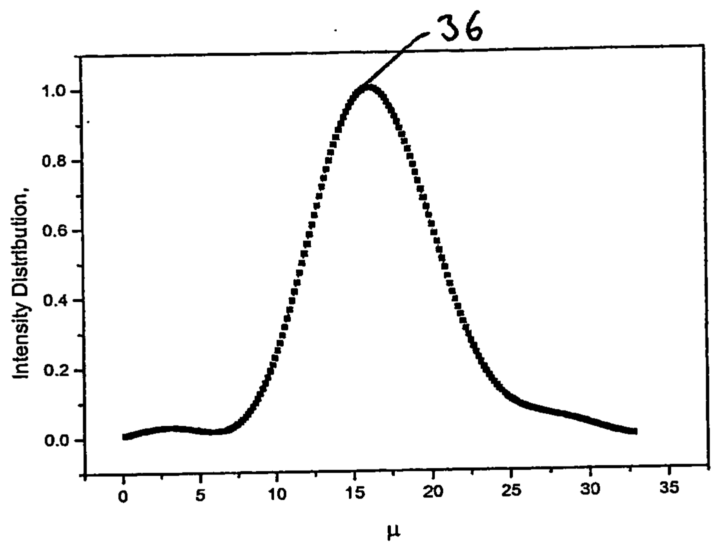


Figure 3g

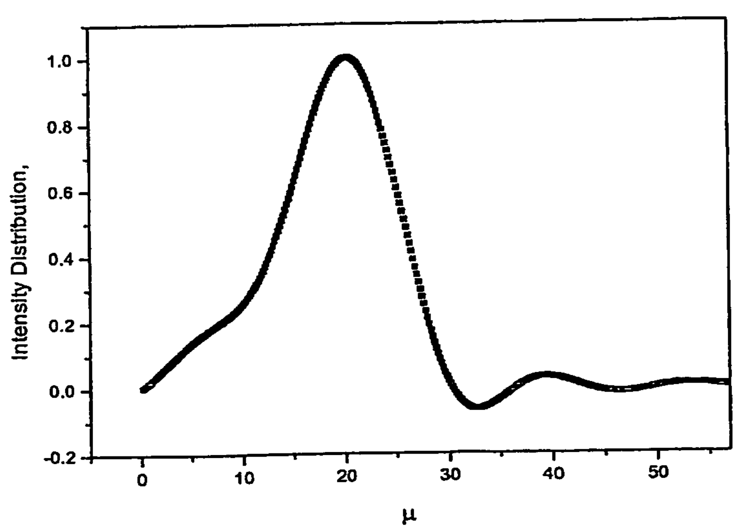


Figure 4a

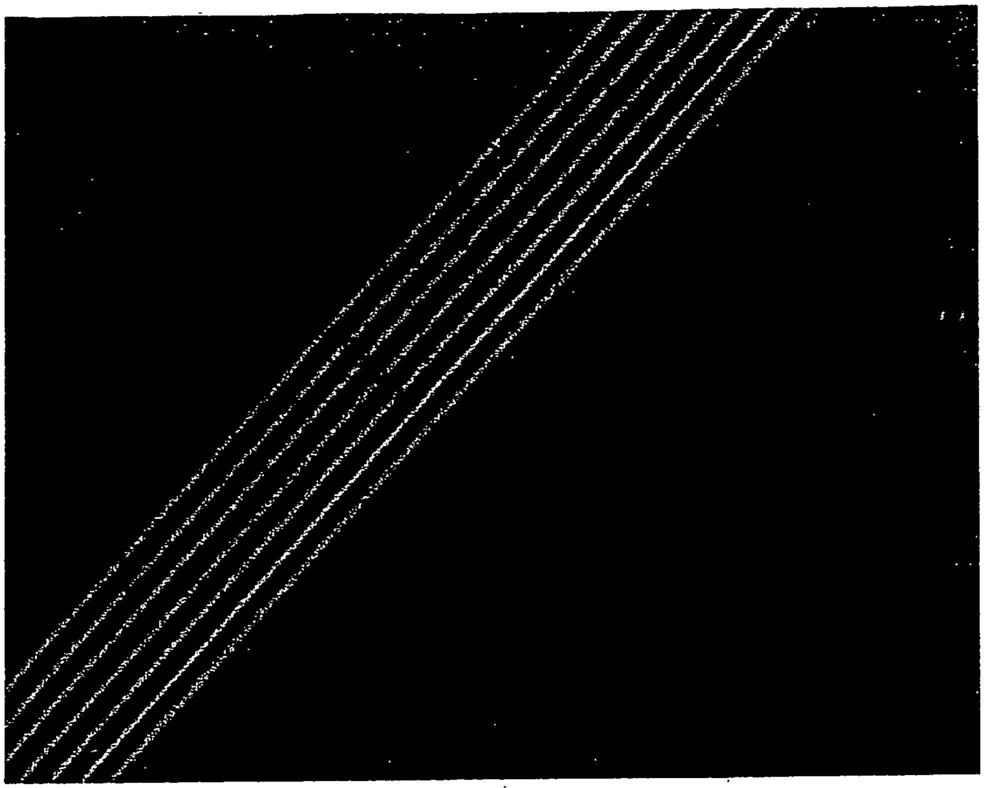


Figure 4b

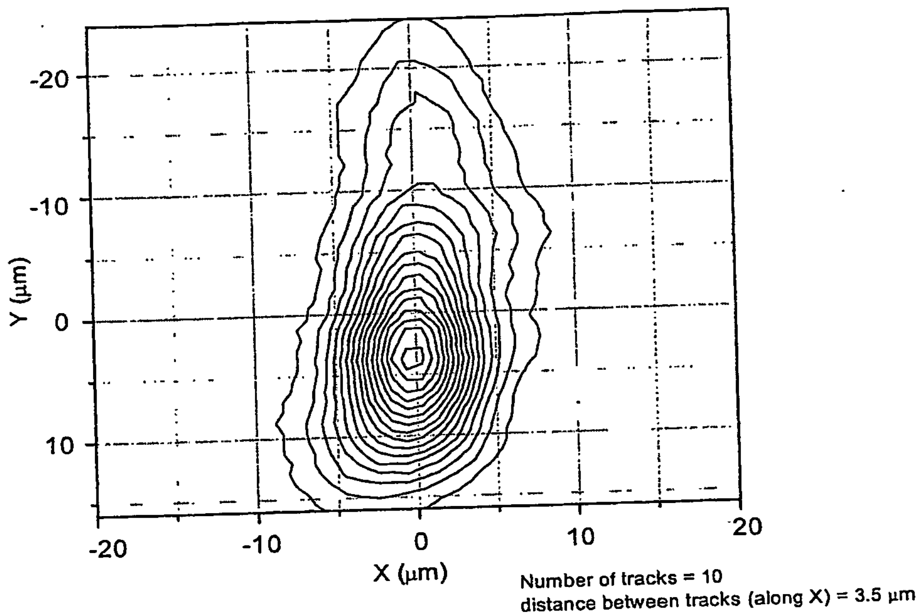

-20
-10
0
10
Y (µm)
-20
-10
0
10
20
X (µm)
Number of tracks = 10
distance between tracks (along X) = 3.5 µm

Figure 4c

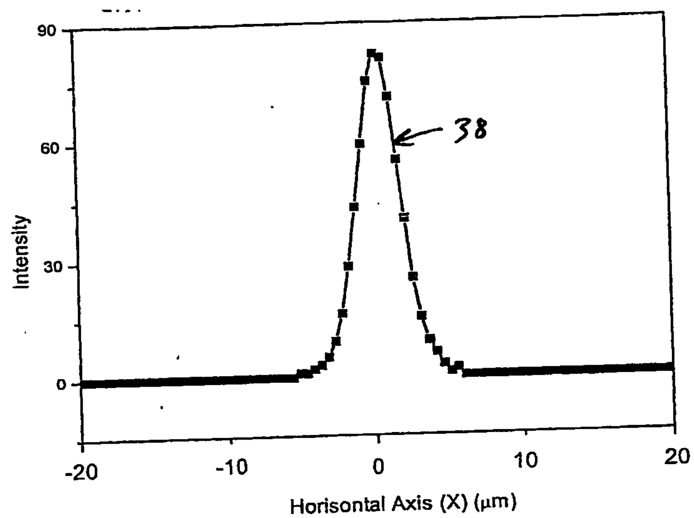


Figure 4d

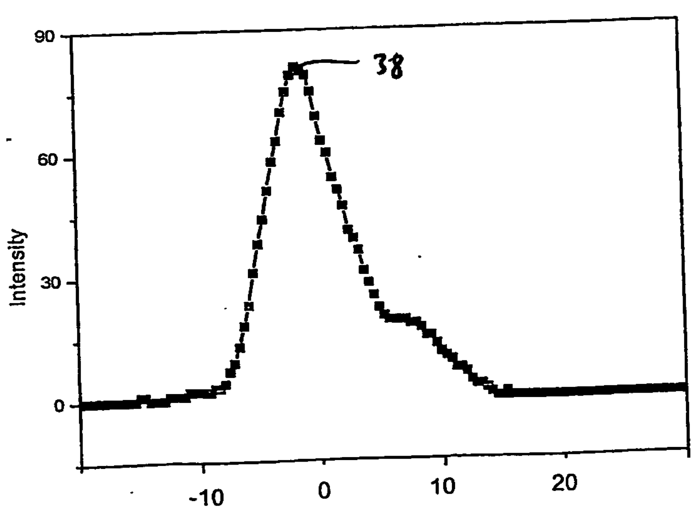


Figure 5a

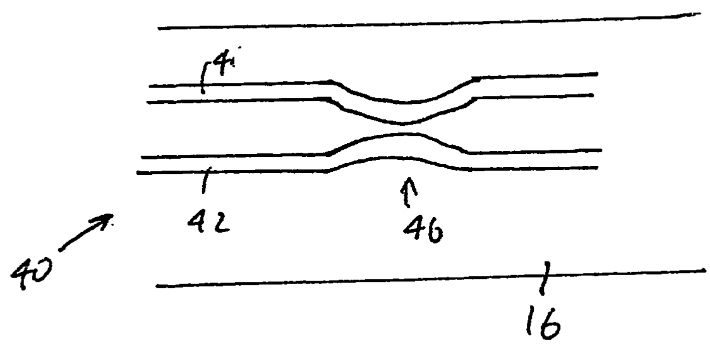


Figure 5b

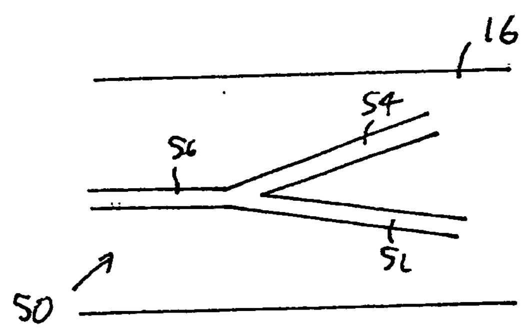


Figure 6

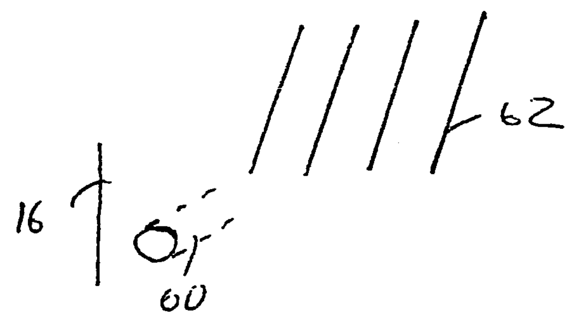
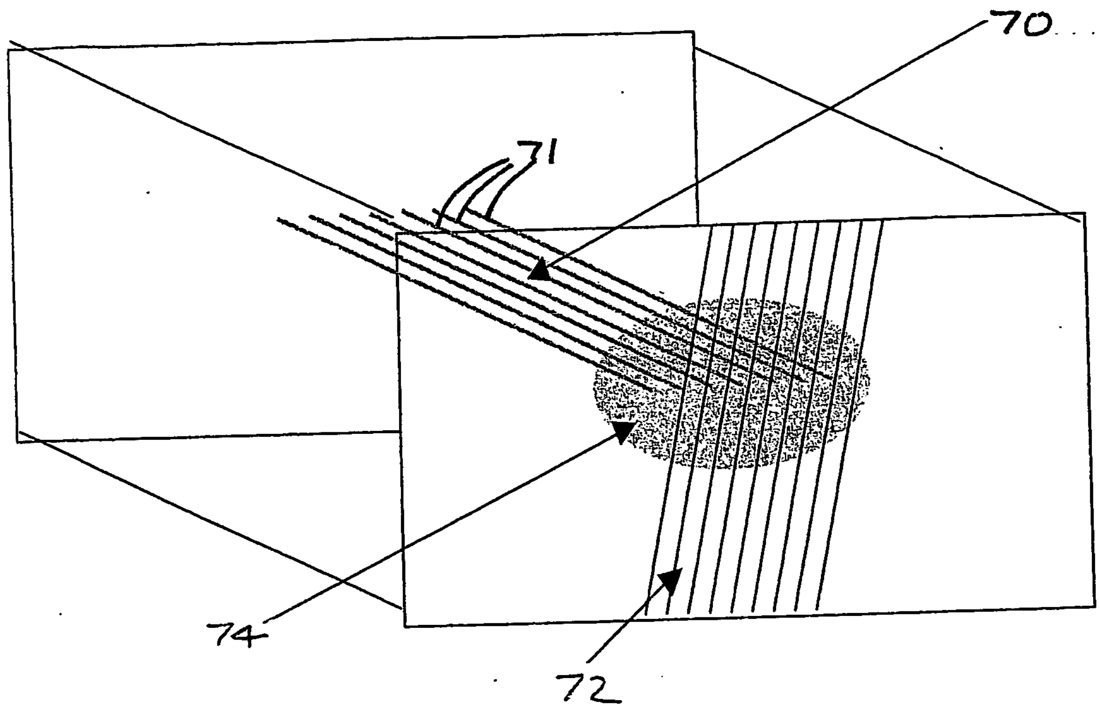


Figure 7



Document made available under the Patent Cooperation Treaty (PCT)

International application number: PCT/GB04/004334

International filing date: 11 October 2004 (11.10.2004)

Document type: Certified copy of priority document

Document details: Country/Office: GB
Number: 0323922.5
Filing date: 11 October 2003 (11.10.2003)

Date of receipt at the International Bureau: 25 November 2004 (25.11.2004)

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b)

World Intellectual Property Organization (WIPO) - Geneva, Switzerland
Organisation Mondiale de la Propriété Intellectuelle (OMPI) - Genève, Suisse